Spectroscopy of Isolated Neutron Stars

or

Hunting for Spectral Lines

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Contents

Two types of emission in INSs:

Non-thermal (magnetospheres, PWNe):

Power-law spectra, no spectral features, info on relativistic electrons

Thermal (NS surface):

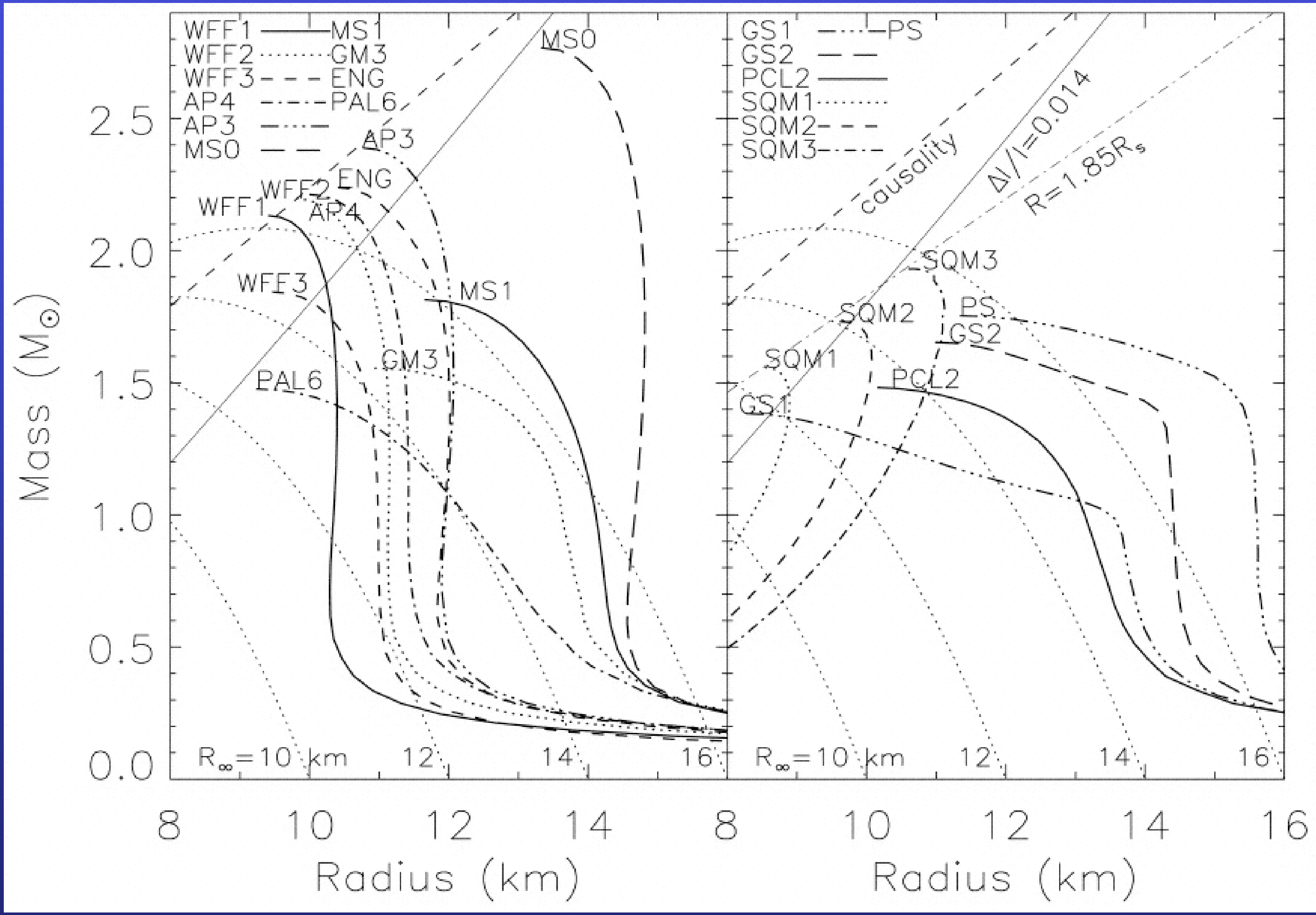
Spectrum depends on physical state (gaseous, liquid, solid), effective temperature, magnetic field, gravity, and chemical composition

Thermal emission: Why important?

Spectral fit ◊ T, F ◊ R/D = [F/(s T^4)]$^{1/2}$ ◊

R ◊ constraints on **E.O.S.**

Mass-radius relations for several EOS (Lattimer & Prakash 2001)



nucleons

exotic composition

Thermal emission: Why important?

Spectral fit ◊ T, F ◊ $R/D = [F/(s T^4)]^{1/2}$ ◊
R ◊ constraints on **E.O.S.**

T (t) ◊ cooling history ◊ internal composition,
baryon superfluidity

Comparison with surface emission models ◊ surface properties (atmosphere/solid), chemical composition, magnetic field, temperature distribution, gravity

Gravitationally redshifted spectral lines ◊ M/R, B

Pulse profiles ◊ M/R, geometry of magnetic field

Expectations: Models for NS Thermal Radiation

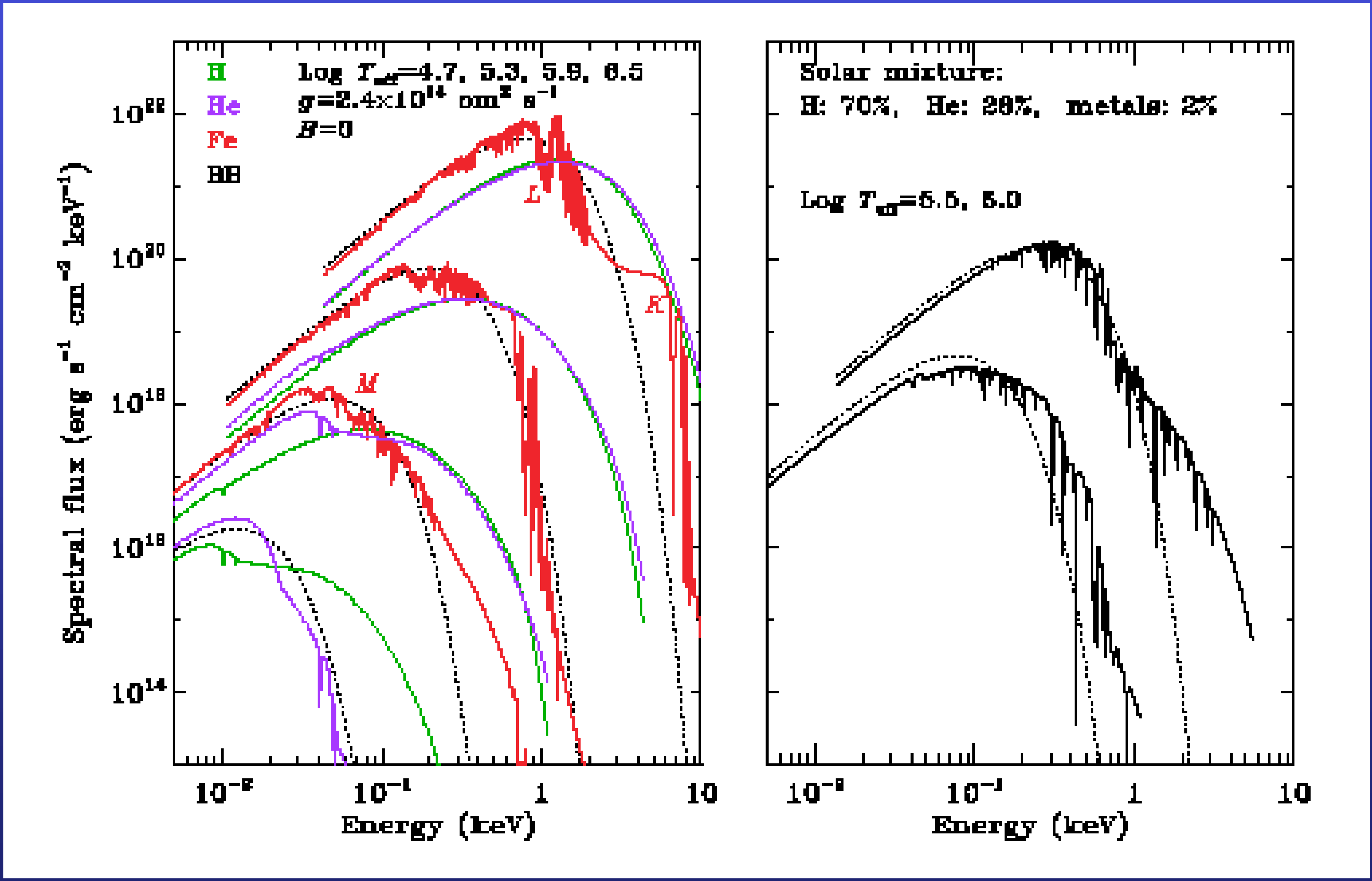
1. Blackbody –-   boring, unrealistic (?)

2. "Nonmagnetic" atmospheres (B << 10^{10} G – e.g., ms-pulsars)

   Hydrogen/Helium --- ionized for observable temperatures, no lines, X-ray spectra harder than blackbodies

   Heavy-element (iron) --- multiple spectral lines

Nonmagnetic NS atmosphere models (Zavlin & Pavlov 2002)



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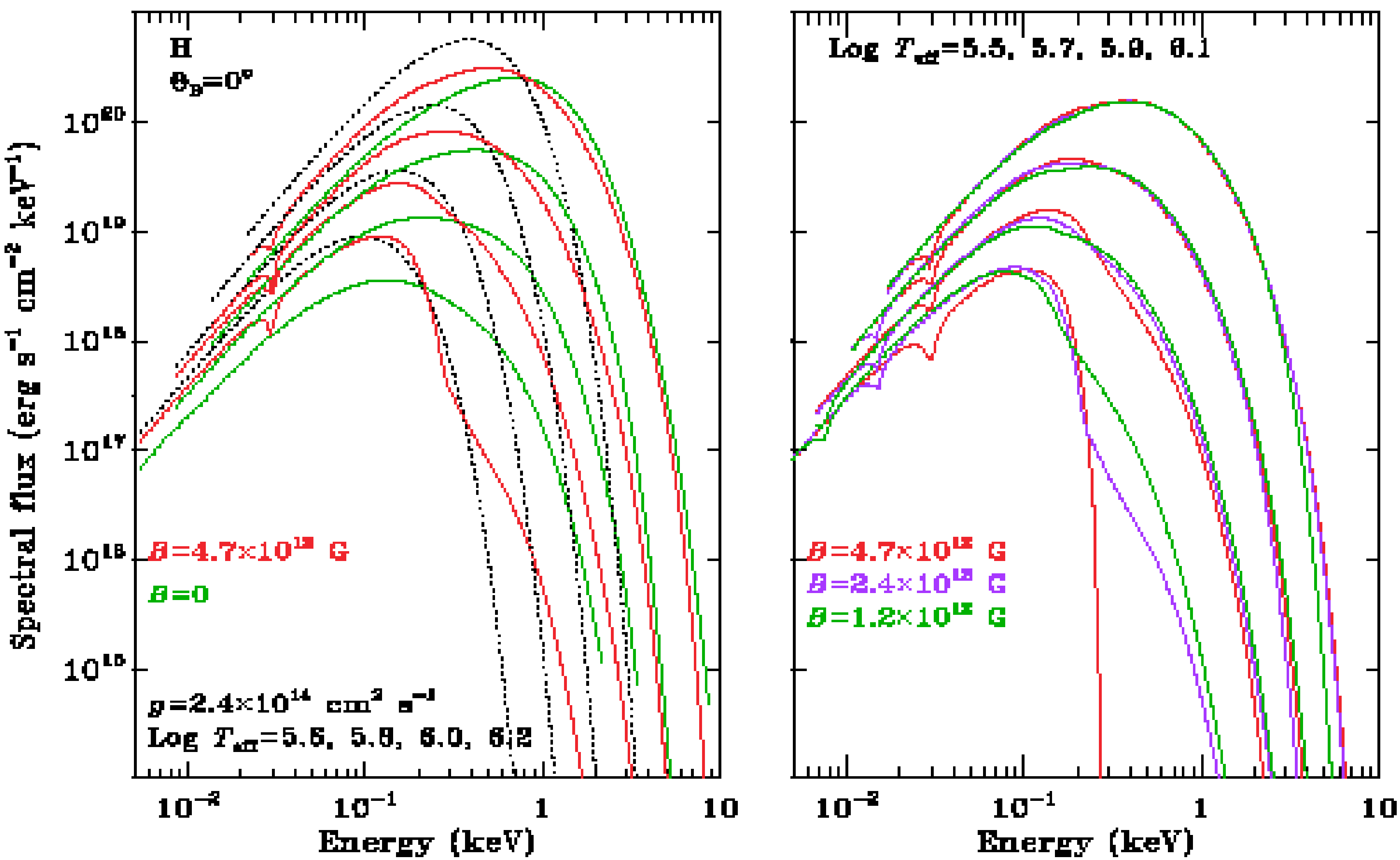
3. Magnetic atmospheres

   Hydrogen --- electron and proton cyclotron lines ($E_{ce} = 1.2\ B_{11}$ keV, $E_{cp} = 6.3\ B_{15}$ keV) from ionized component; atomic lines get in X-ray range for superstrong magnetic fields

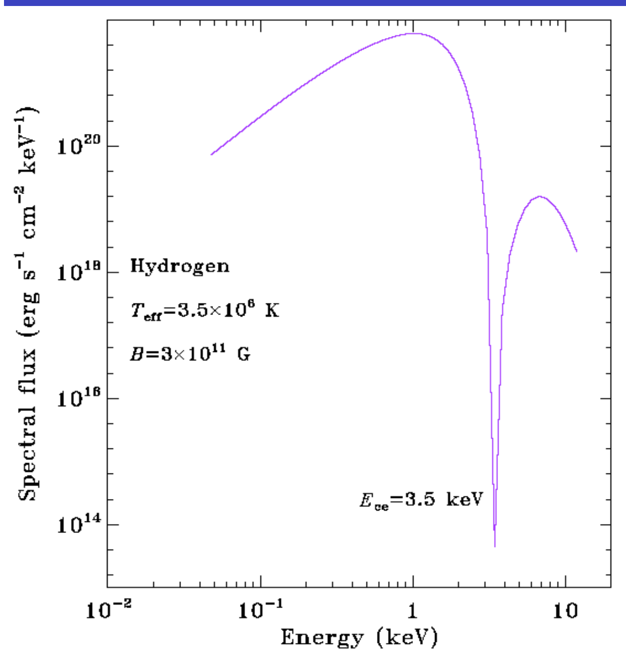
   Iron --- multiple spectral lines

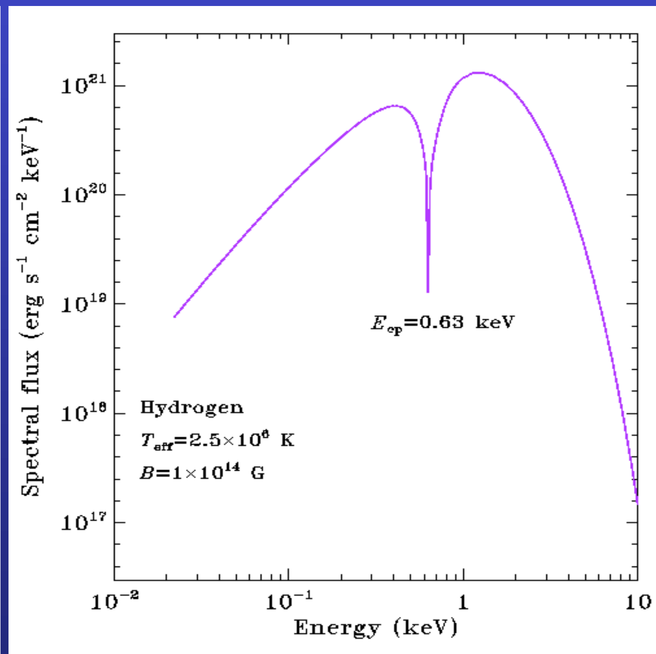
Magnetic Hydrogen atmospheres (Pavlov et al. 1995)

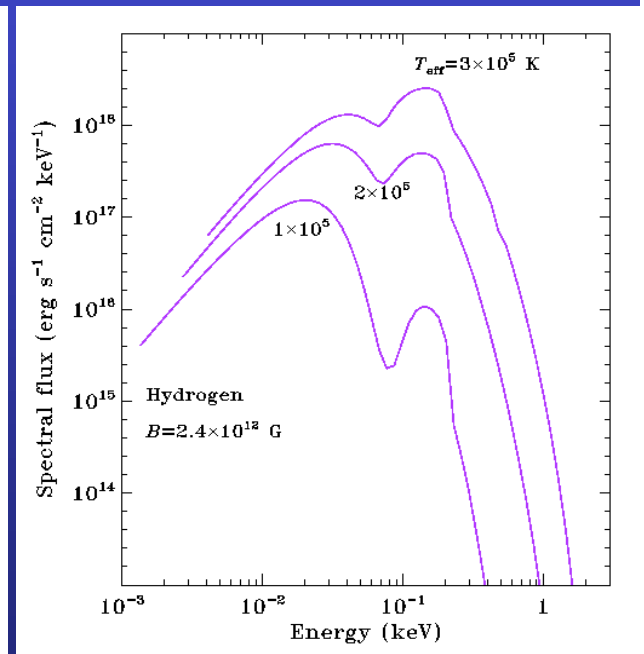


Lines in magnetic Hydrogen atmospheres (Zavlin & Pavlov 2002)

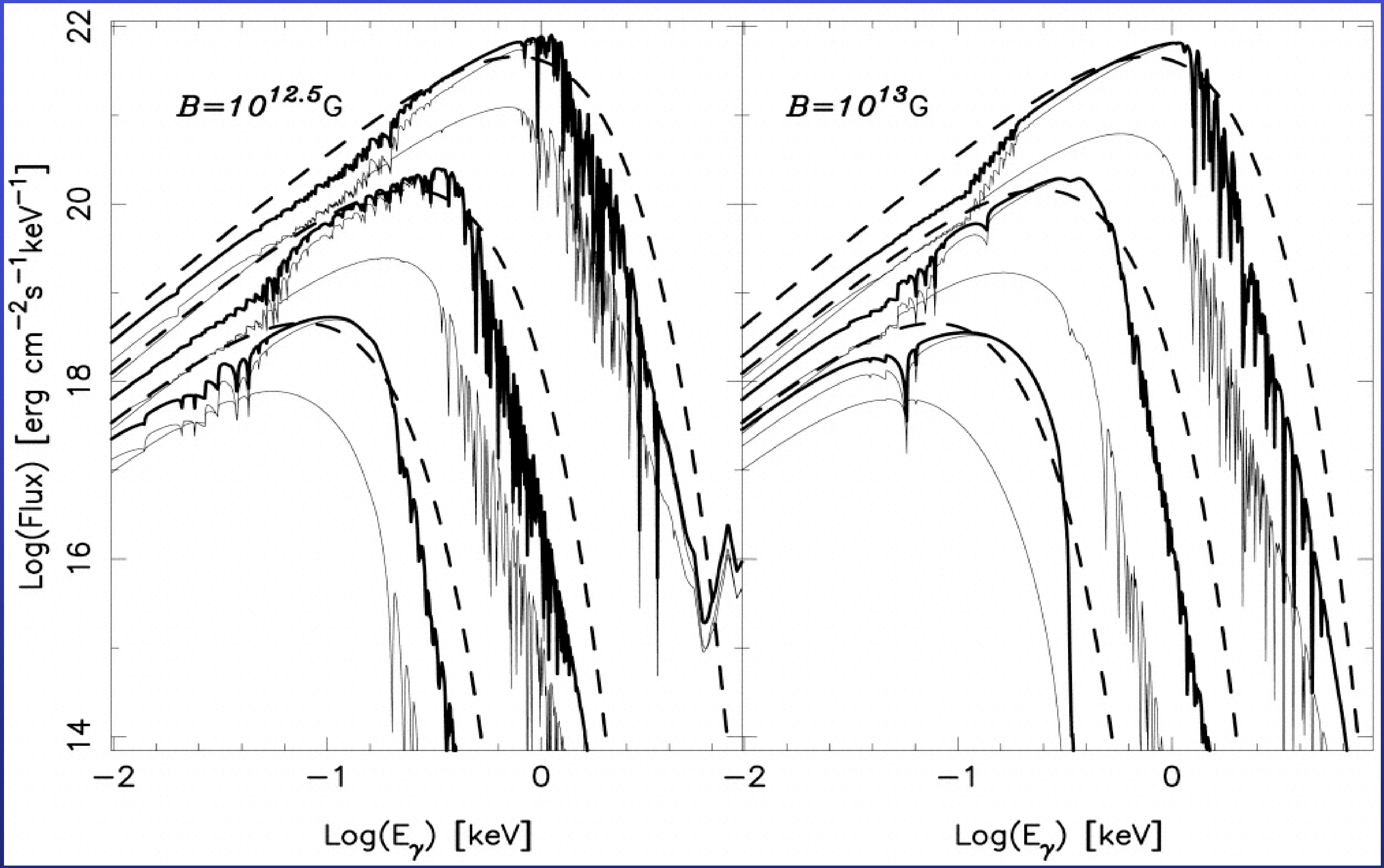
Electron cyclotron line	**Proton cyclotron line**	**Hydrogen atomic lines**
B=3e11 Gauss,	**B=1e14 Gauss,**	**B=2.4e12 Gauss,**
Teff= 3.5e6 K	**Teff=2.5e6 K**	**Teff=1e5, 2e5, 3e5 K**







Magnetic iron atmospheres (Rajagopal, Romani, Miller 1997)



Log Teff = 5.5, 6.0, 6.5

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4. Solid/liquid surface --- no reliable models

OBSERVATIONS

Different kinds of thermally-emitting NSs:

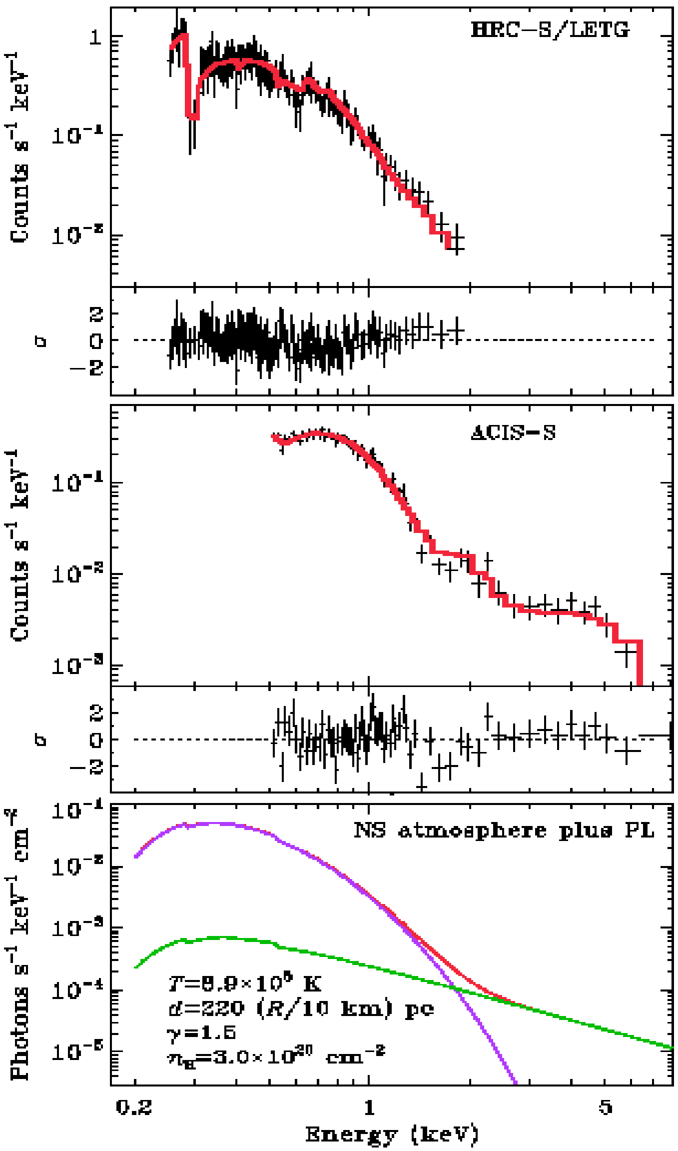
I. ACTIVE, ROTATION-POWERED PULSARS

Best targets: **middle-aged** (10 – 1000 kyr) pulsars:
Thermal from whole surface (+ polar caps), in soft X-rays
EUV; non-thermal in hard X-rays, optical

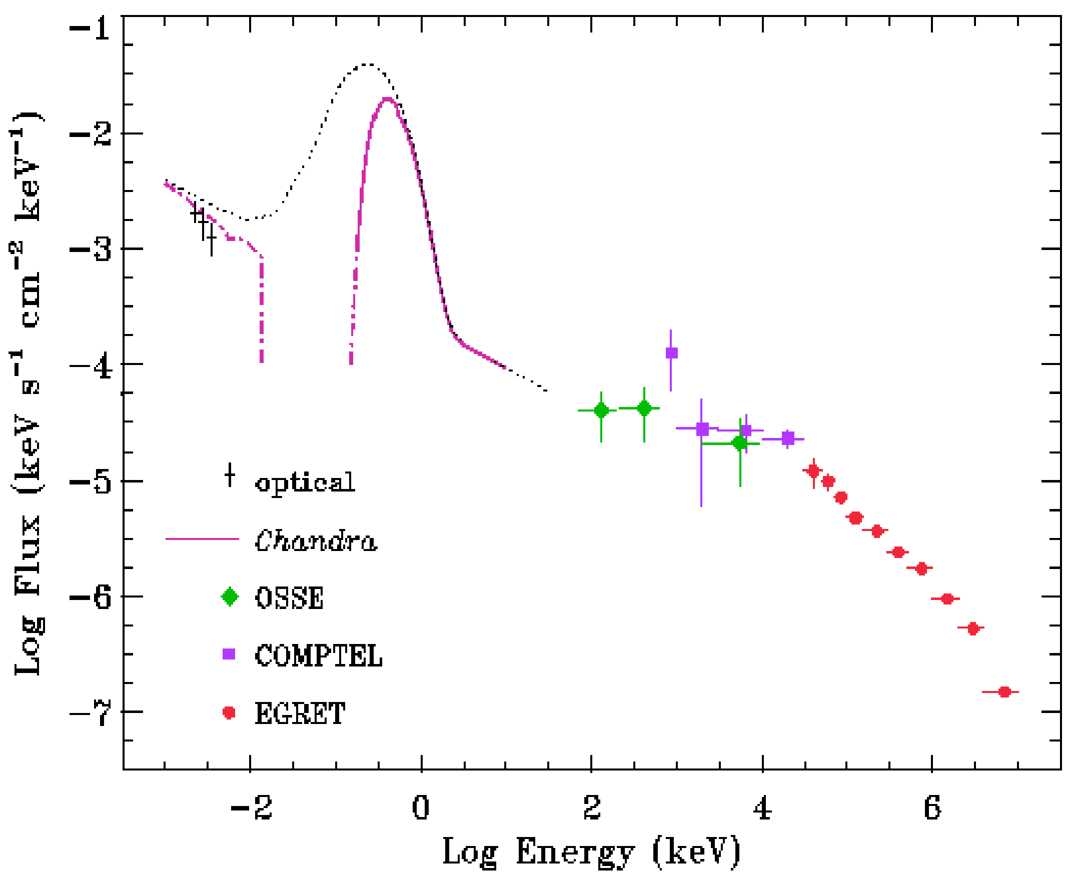
- No spectral lines seen
- H atmospheres require too small distances or too large radii (in most cases)
- Fairly good fits are obtained with two blackbodies + power-law

Chandra: H atmosphere
[kT_{eff}=60 eV, R=15 km]
+ Power-law [Γ=1.5]

Vela PSR (t_c=P/2Pdot=11 kyr)



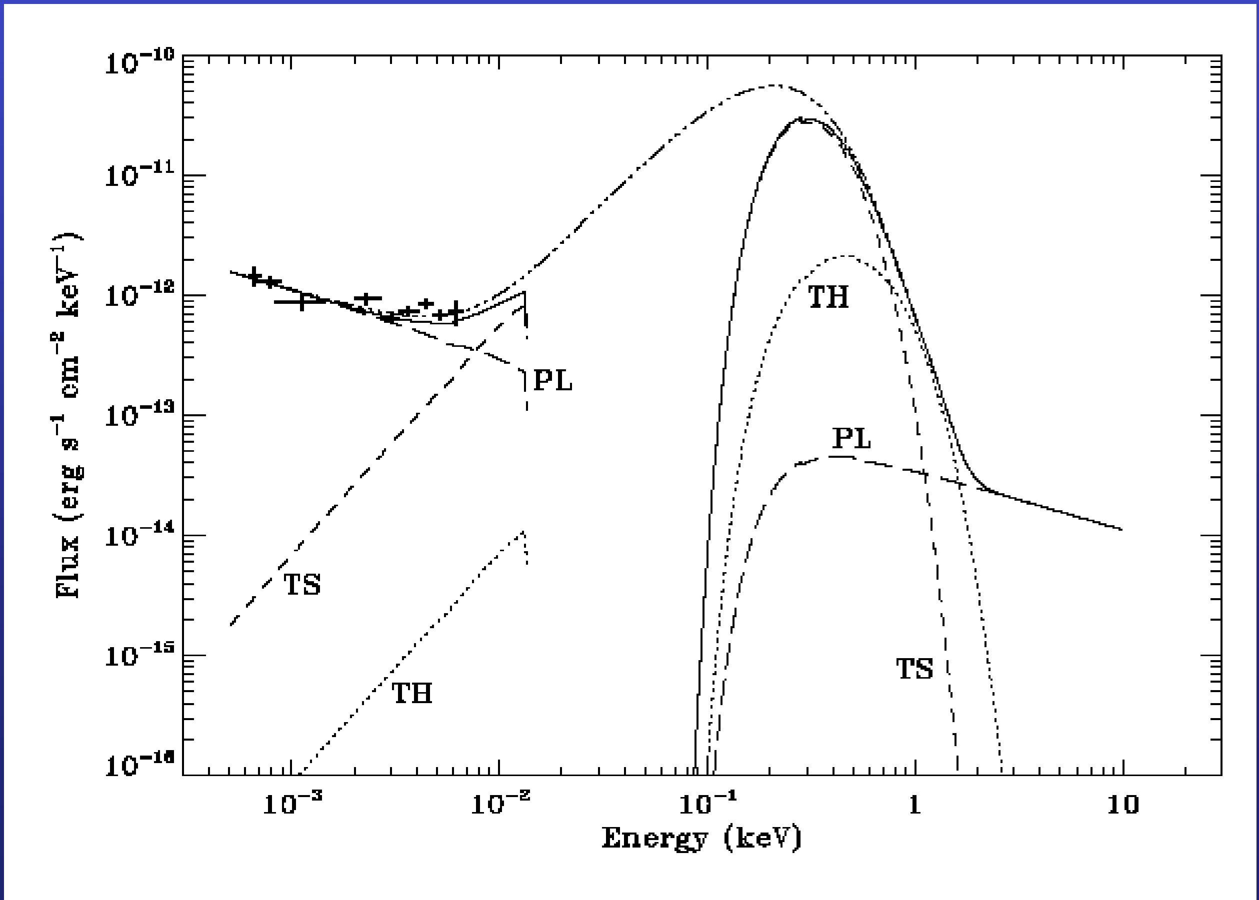
Optical through gamma-rays:
thermal dominates in 0.02-2 keV



PSR B0656+14 (t_c = 110 kyr)

Chandra ACIS and HRC/LETG + optical (Koptsevich et al. 2001; Marshall et al 2002; Zavlin et al. 2003)

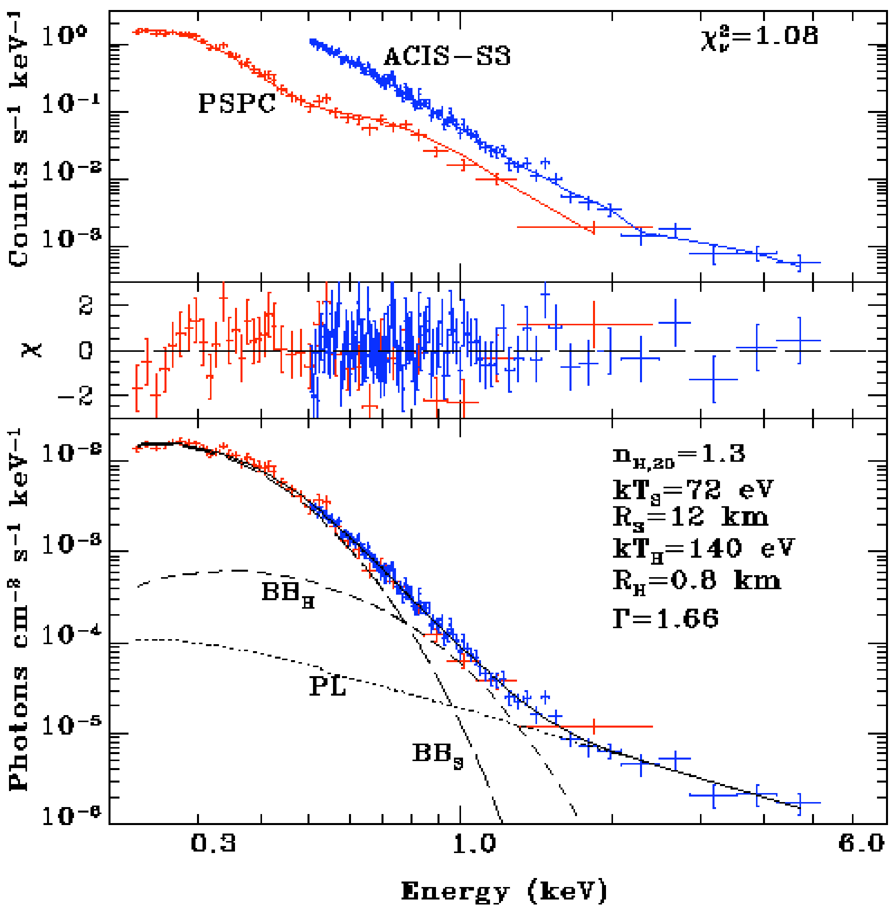
BBsoft (kT=73 eV, R=15 km) + BBhard (kT=138 eV, R=1 km) + PL (Γ=1.5)

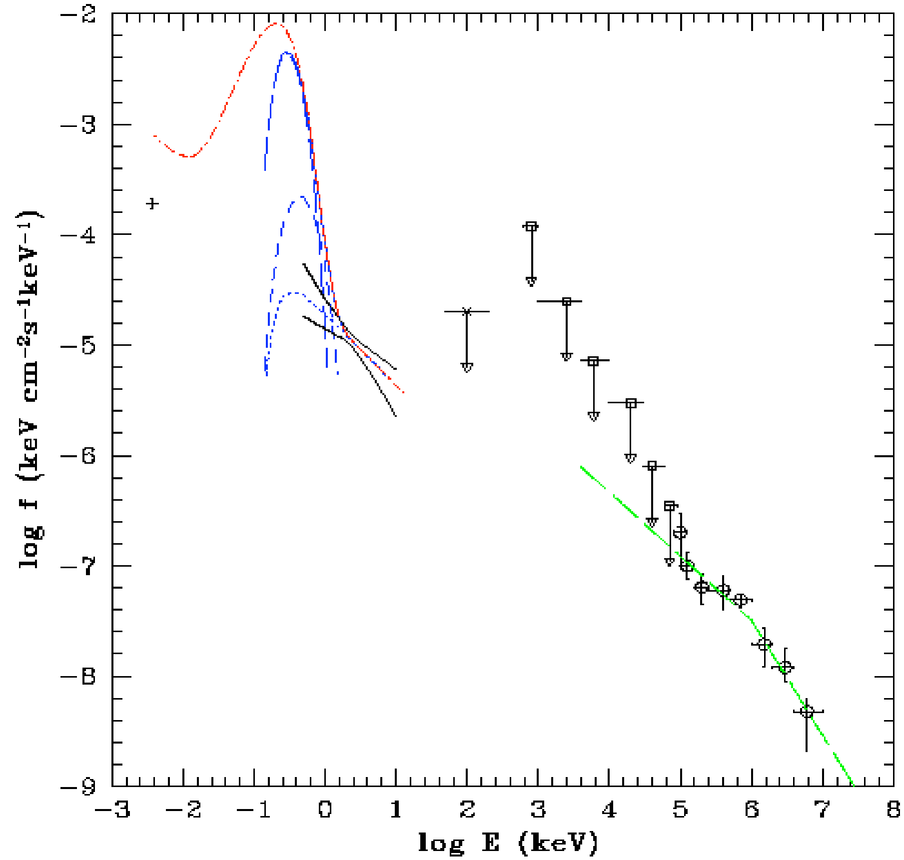


PSR B1055-52 (t_c = 500 kyr)

Chandra/ACIS + ROSAT/PSPC:
BBsoft [kT=72 eV, R=12 km] +
BBhard [kT=140 eV, R=0.8 km]
+ Power-law [Γ=1.7]

Optical through gamma-rays:
(thermal in ~0.02 – 2 keV)





II. RADIO-QUIET NEUTRON STARS

"The only good pulsar is a dead one"

1. Central Compact Objects (CCOs) in SNRs

(Cas A, Pup A, "Vela Junior", … -- 9 objects)

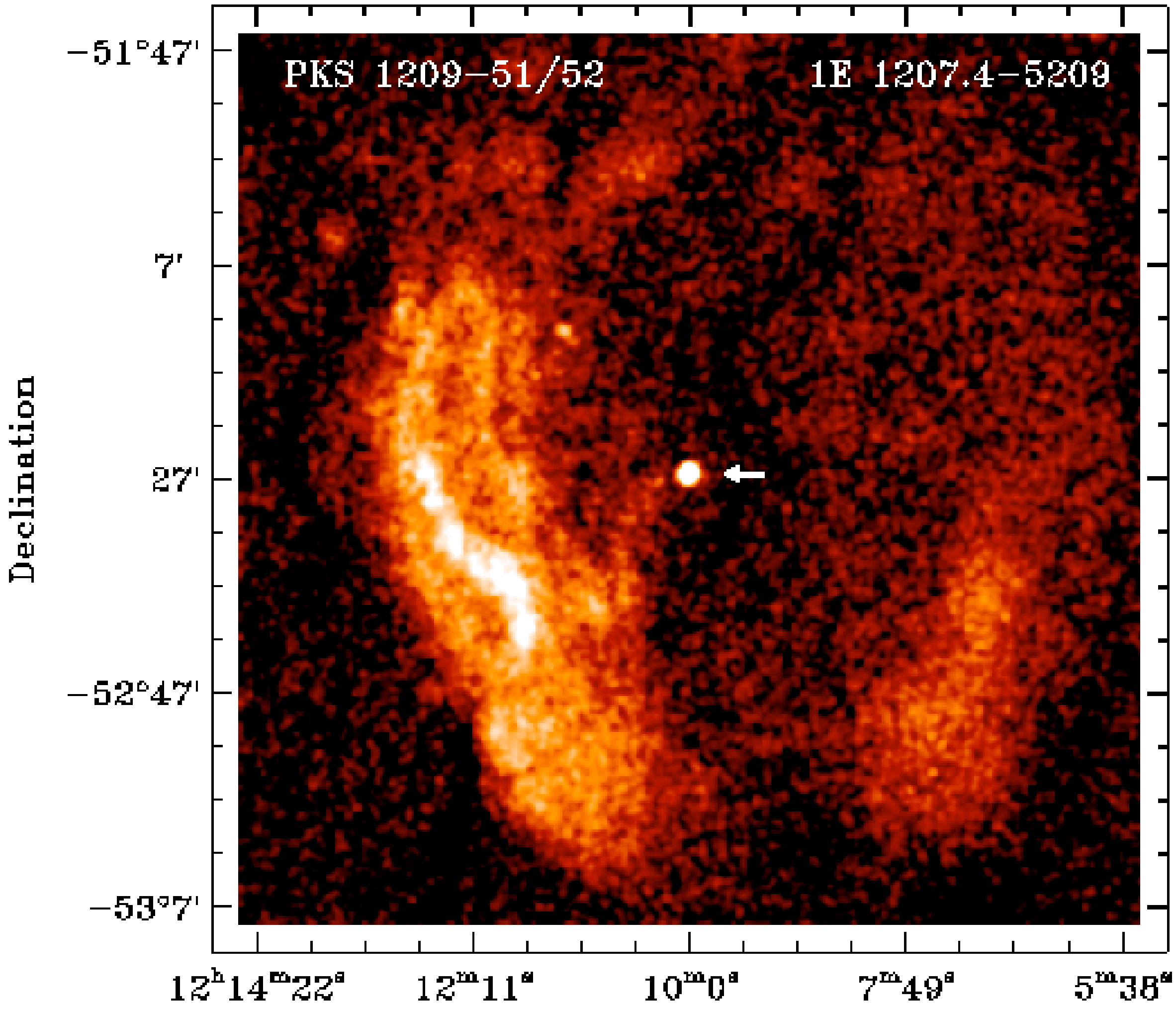
No radio/gamma/optical, thermal soft X-rays [$kT_{BB} = 0.25 – 0.5$ keV, $R_{BB} = 0.3 – 2$ km (!)]

Hydrogen NS atmosphere fits: decrease T to 0.14 – 0.3 keV, increase radius to 1 – 12 km (>10 km in 2 objects only – not a universal recipe to get a reasonable NS radius; CCOs are not all the same objects?)

At least some of the CCOs are neutron stars.

1E 1207.4-5209 in G296.5+10.0

Discovered with Einstein (Helfand & Becker 1983), studied with EXOSAT, ROSAT, ASCA, Chandra, XMM



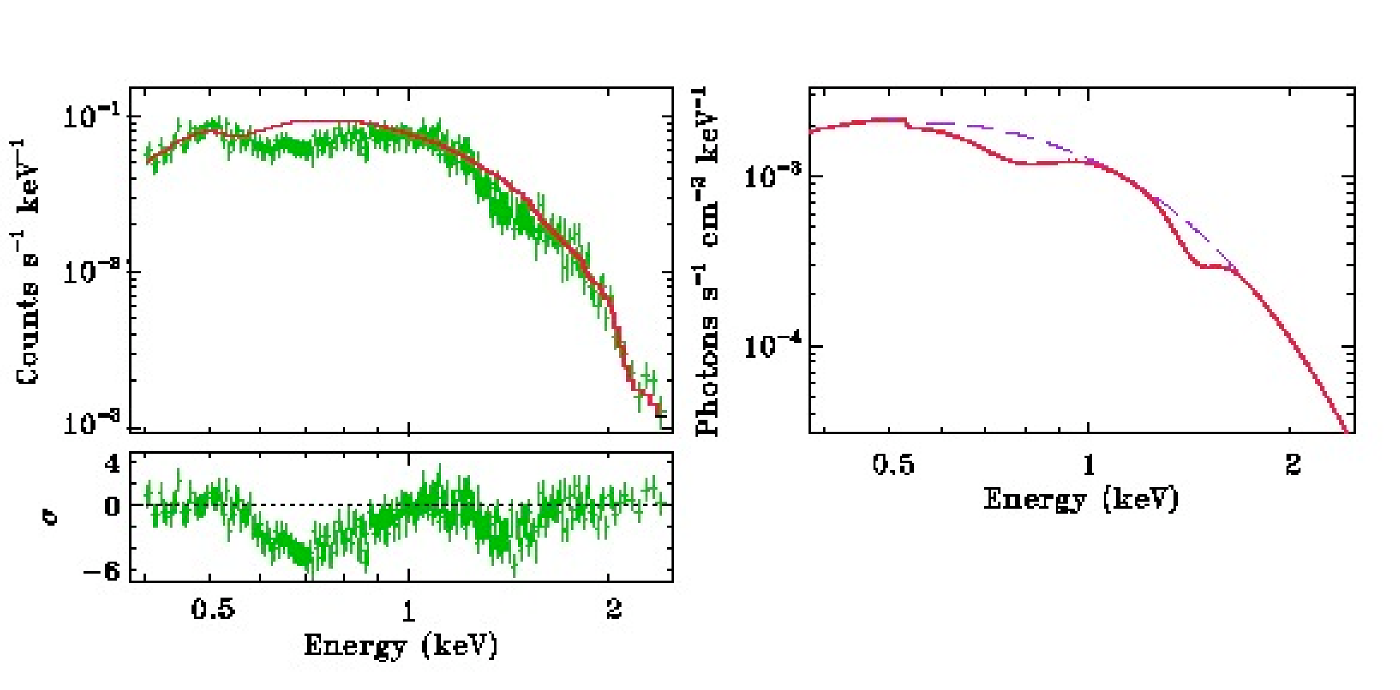
SNR: distance = 2.1 (+1.8, -0.8) kpc,

age = 3 – 20 kyr

Chandra observations (Zavlin et al. 2001; Pavlov et al. 2002; Sanwal et al. 2002)**:**

P=424 ms (a NS!), t_c=P/(2 Pdot) = 300 kyr (? vs. 3 – 20 kyr for SNR), centered-dipole magnetic field = $3*10^{12}$ Gauss

Spectrum: Two broad absorption features around **0.7** and **1.4 keV** (!)



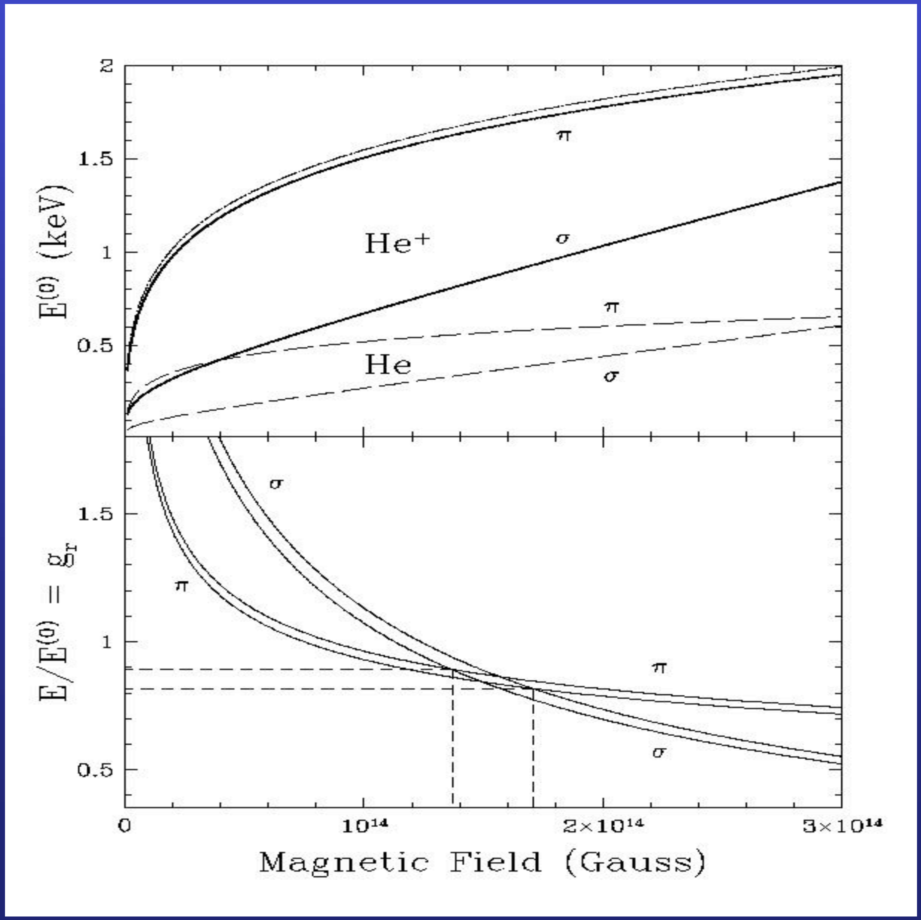
XMM: Depths of the features vary with phase; 0.7 keV feature shows fine structure (Mereghetti et al. 2002)

Interpretations of the features:

Cyclotron harmonics? **Unlikely** – too small B required

Hydrogen lines in superstrong magnetic field? **No**

Helium lines in superstrong magnetic field? **May be**



$B = (1.4 – 1.7)*10^{14}$ G

$z = 0.12 – 0.23$

$R/M = 8.8 – 14.2$ km/M_{sun}

He-like Oxygen and/or Neon ions in B~10^{11} – 10^{12} G ? (Hailey & Mori 2002) **May be**

For instance:

OVII (two lines) B = 5.5 – 7.5 * 10^{11} G, z = 0.06 – 0.21

Results strongly depend on identification of the features

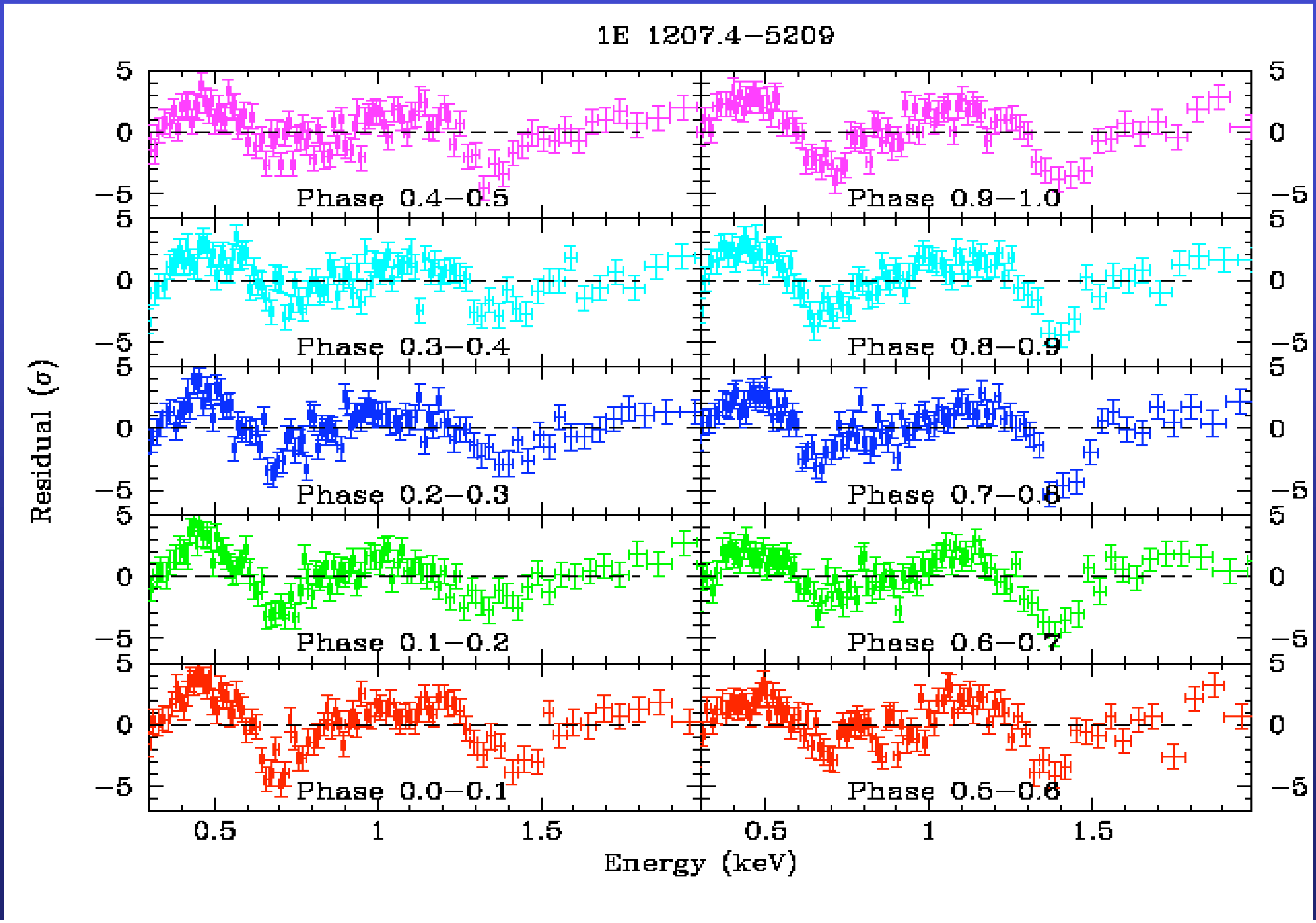
High-resolution spectroscopy needed

Second XMM observation (260 ks):

Allows for phase-resolved spectroscopy with moderate energy resolution (EPIC-pn) and high-resolution phase-integrated spectroscopy (RGS)

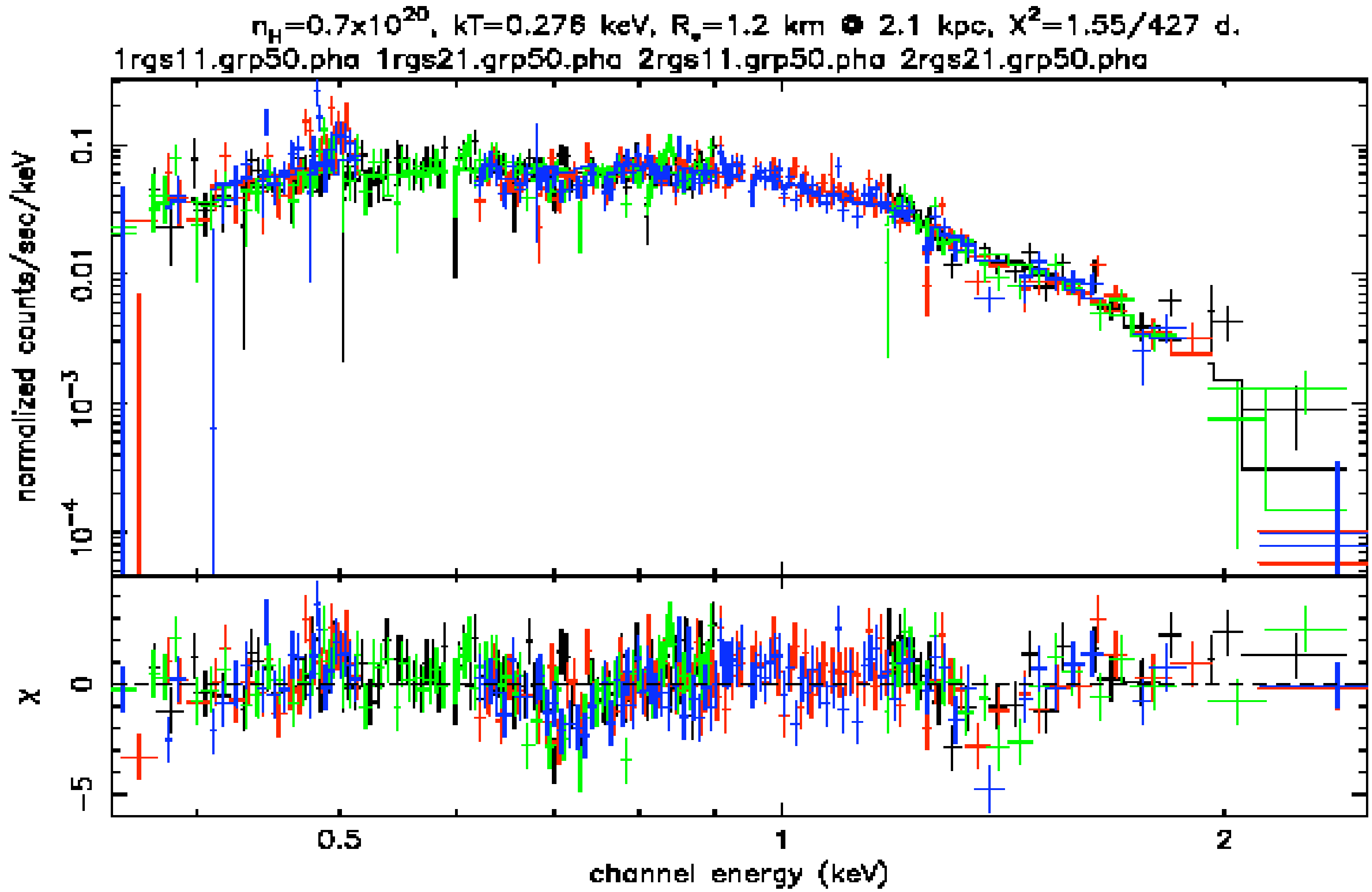
Phase-resolved, medium-resolution spectroscopy (EPIC-pn):

The 0.7 keV line varies with phase, shows a substructure at phase 0.5-0.6 – perhaps a blend of different transitions



High-resolution, phase-integrated spectroscopy (RGS):

Not impressive (high background; low sensitivity – **Con-X needed, with high resolution in both energy and time**)



2. **“Dim” Isolated Neutron Stars** (7 objects)

No radio, no gamma, no power-law component in X-rays;

very soft thermal spectra [kT = 40 – 100 eV from X-rays];

periods firmly known for 2 objects [P = 8.4 and 10.3 s];

optical emission detected from 3 objects (~Rayleigh-Jeans)

– look most promising for analysis of thermal NS emission.

However, things are not that simple in real life…

RX J1856.5-3754

Best studied "dim" neutron star

Discovered with ROSAT (Walter et al. 1996)

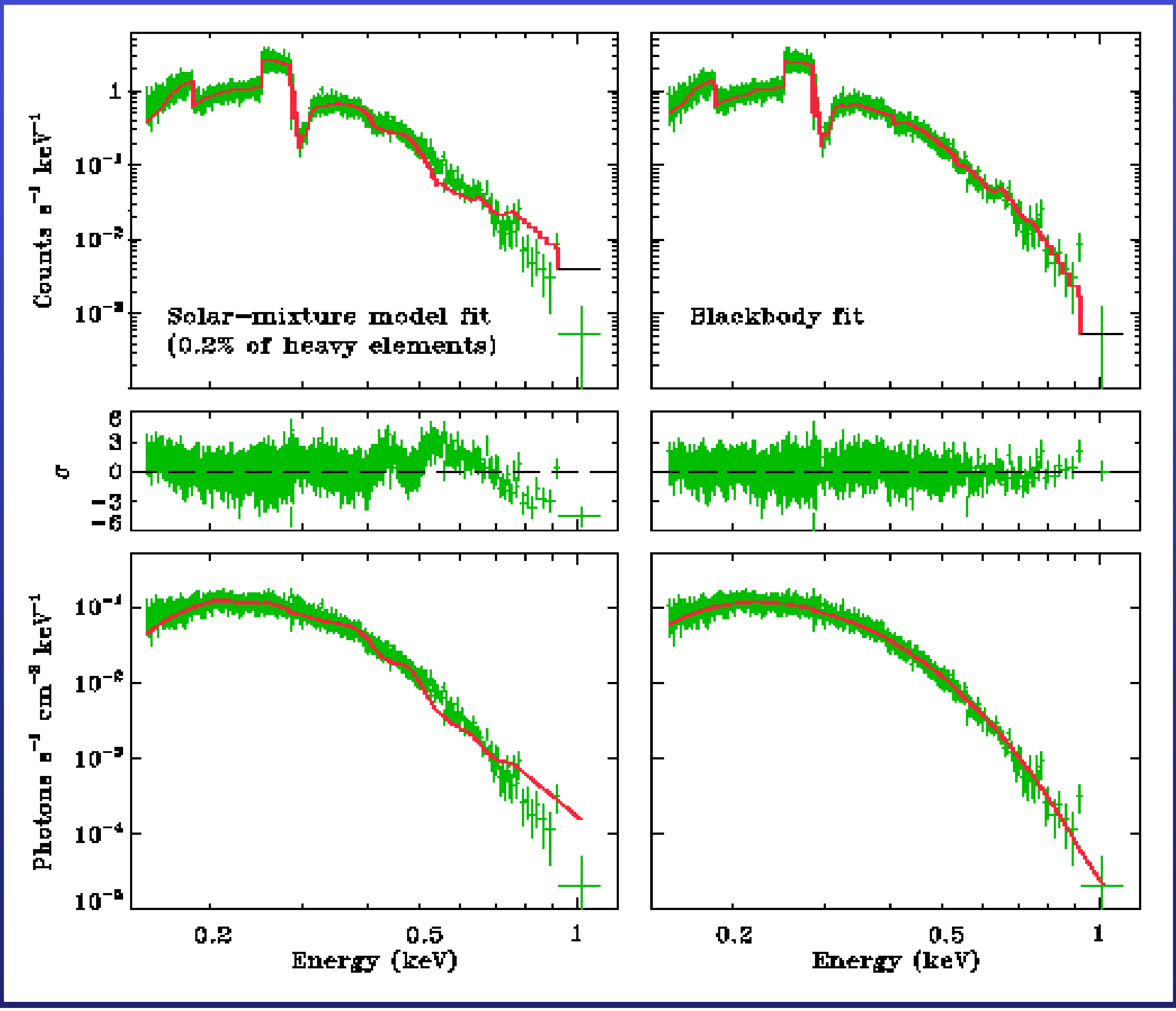
Studied with ROSAT, EUVE, HST, Chandra (505 ks!), XMM (refs. in Burwitz et al. 2002)

Distance = 117+/-12 pc from optical parallax

No pulsations found (pulsed fraction < 2% for P>20 ms)

All available NS atmosphere models do not fit the X-ray spectrum.

Simple blackbody model provides a fair fit.



kT=63.5+/- 0.2 eV
R=4.4+/-0.1 km

Is it a NS at all?

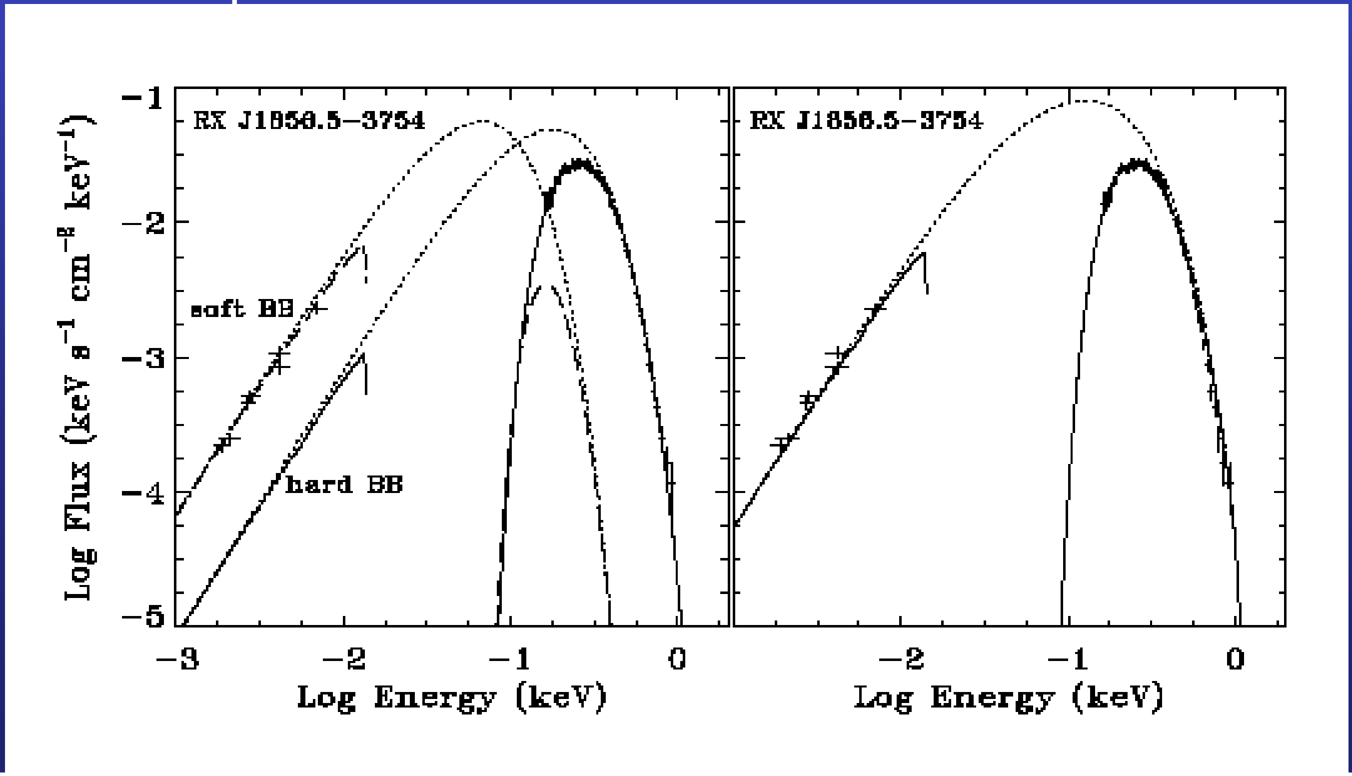
A quark star?
(Drake et al. 2002)

BUT, there is an optical/UV spectrum, too. Extension of the X-ray blackbody fit underpredicts the optical flux!

Possible solutions:

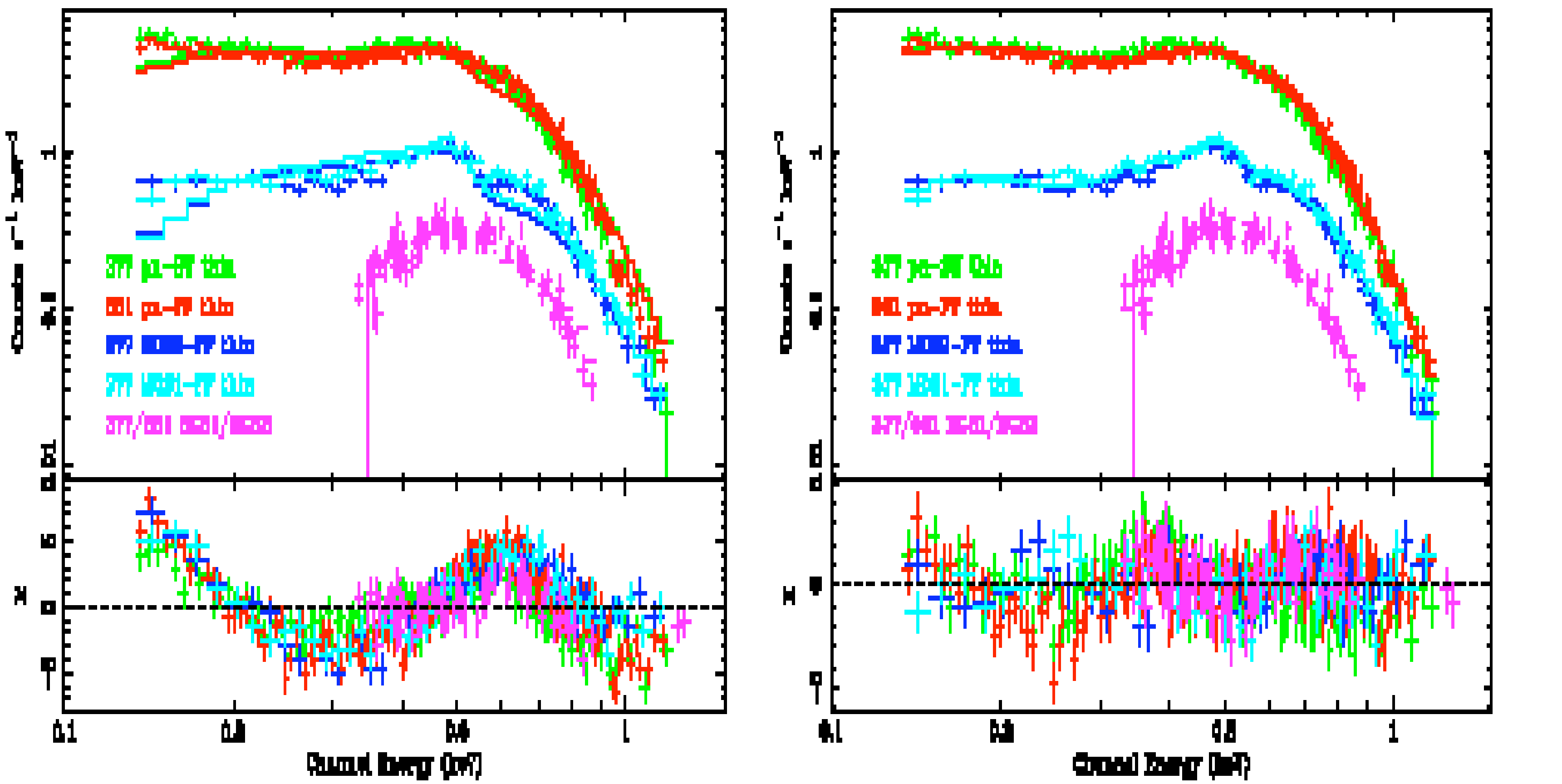
1. Nonuniform temperature: X-rays from a hot polar cap , optical from the whole (colder) surface --- a ms-pulsar? To be checked…
2. NS surface is solid, with high reflectivity, low emissivity in X-rays --- emission models are poorly known for such exotic solids

Two temperatures Continuum T distribution



RBS 1223 (J130848+212708) – one more dim INS

P=10.3 s, kT=87 eV; **broad absorption line at 300 eV?** **Proton cyclotron line in B = 6e13 G ???** (Haberl et al. 2003)



3. Anomalous X-ray Pulsars, Soft Gamma Repeaters [Magnetars? ~10 objects]

Low-resolution spectroscopy: Blackbody [$kT = 0.4 - 0.6$ keV, $R = 1 - 7$ km] + Power law ($\Gamma \sim 3$)

or multi-temperature blackbody…

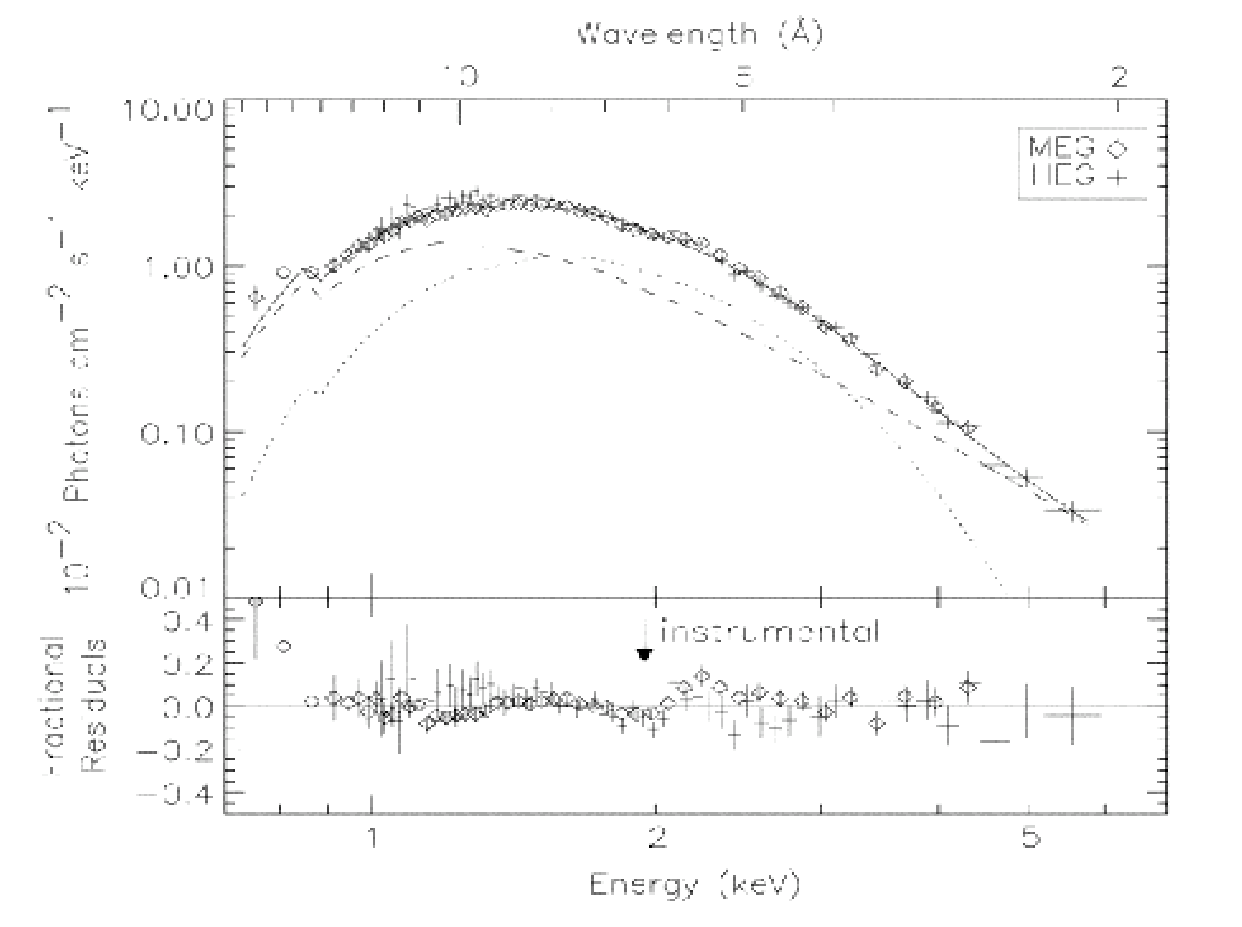
or H atmosphere in a superstrong magnetic field ($kT \sim 0.2 - 0.3$ keV, $R \sim 10 - 50$ km).

Presence of thermal component is very plausible; can be explained by dissipation of superstrong magnetic field and surface heating from the magnetosphere (Thompson et al. 2002).

High-resolution spectroscopy: first results discouraging

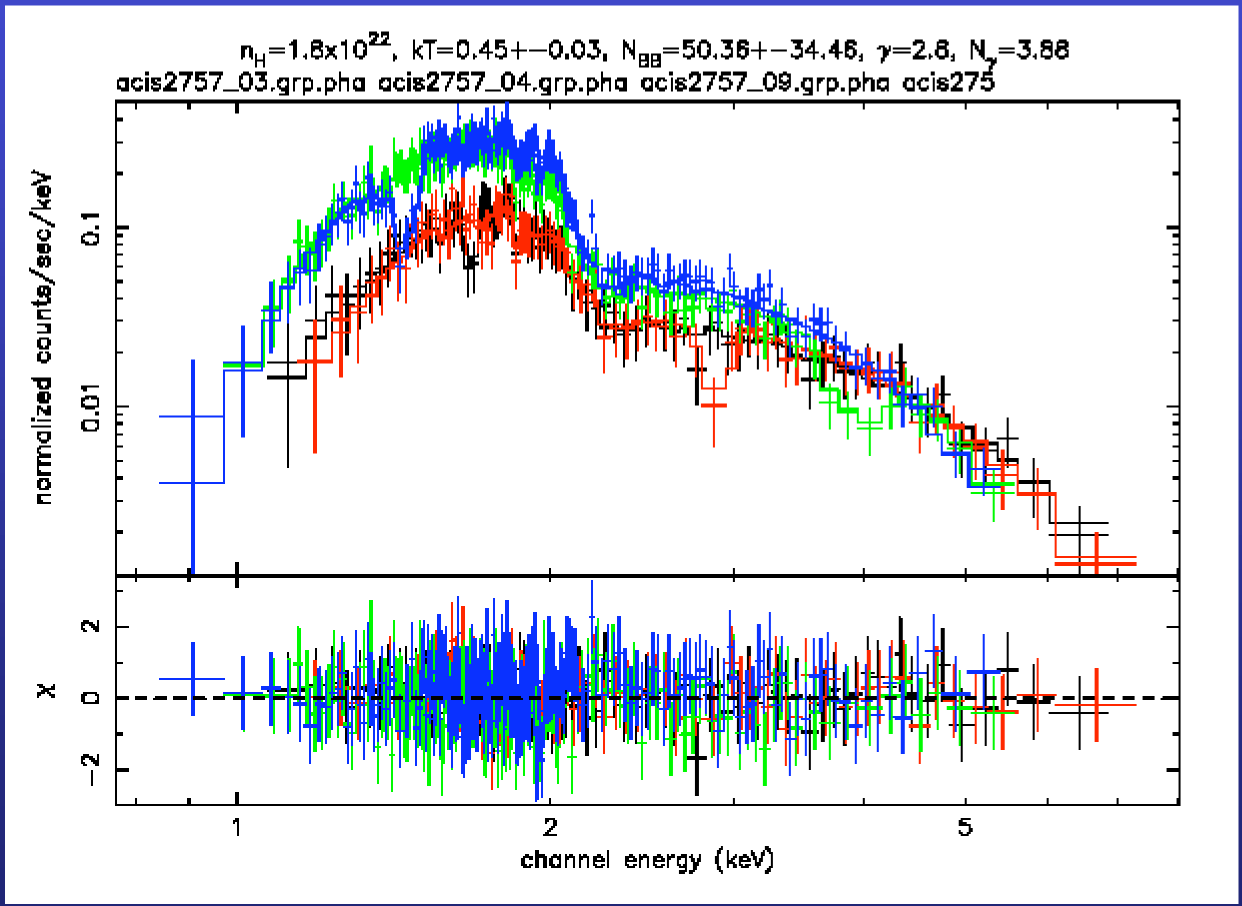
4U 0142+61: the brightest AXP (Juett et al. 2002)

Chandra HETG: **no lines**; BB (kT=0.42 keV) + PL (Γ=3.3)



RXJ 170849-400910 – bright AXP

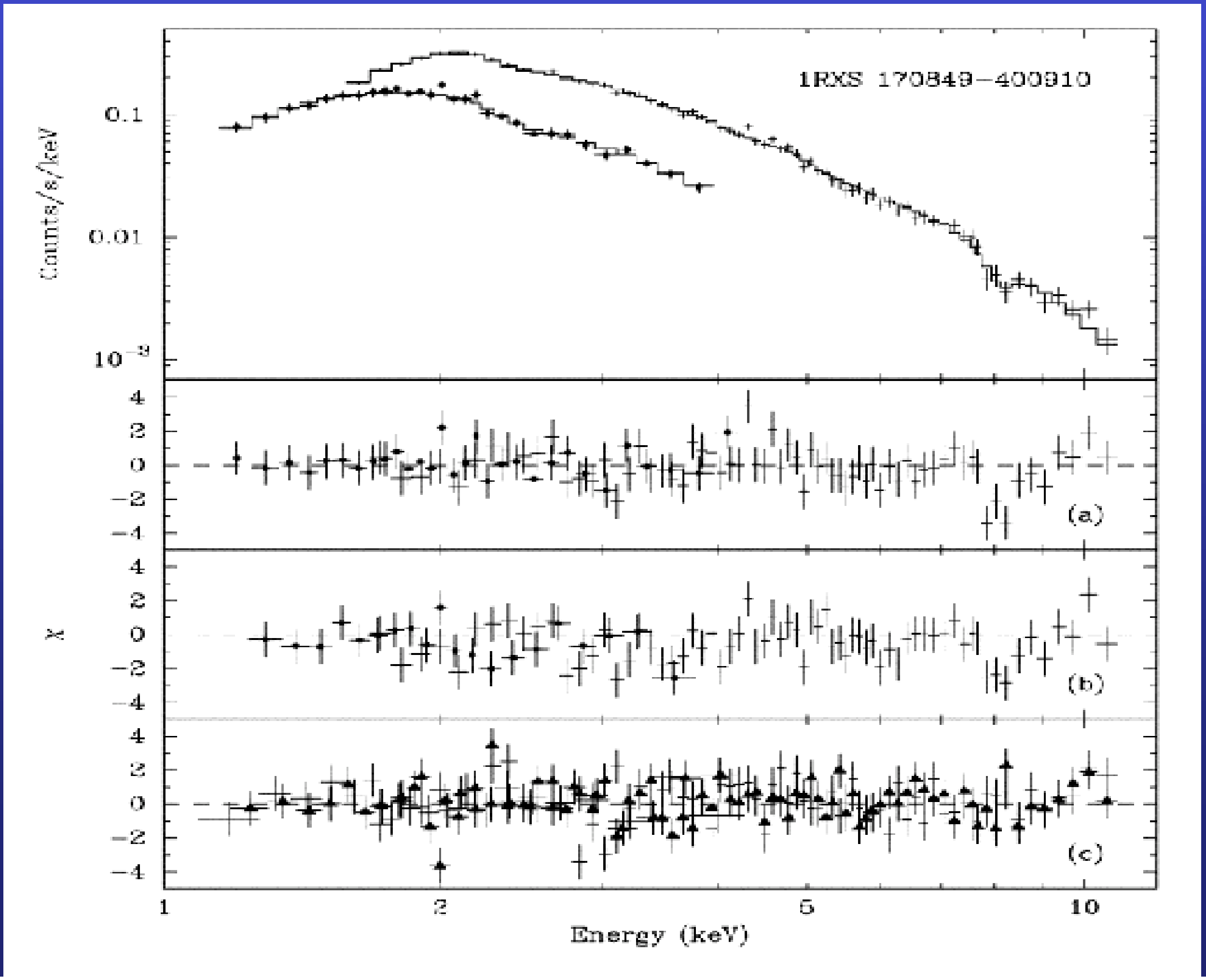
Chandra HETG (Sanwal et al. 2003):
no lines, BB (kT=0.45 keV) + PL (Γ=2.6)



BUT…..

Beppo-SAX observation of J1708 shows a line at **E=8 keV** at some phases (Rea et al. 2003).

Proton cyclotron line in B=1.6e15 G ??
Electron cyclotron line in B=9e11 G ??

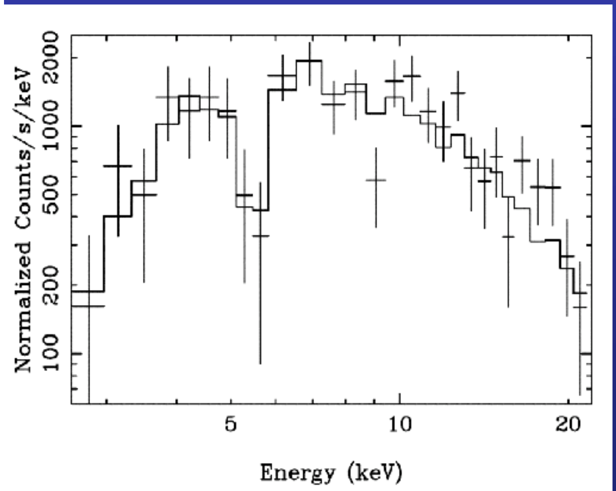


SGR 1806-20

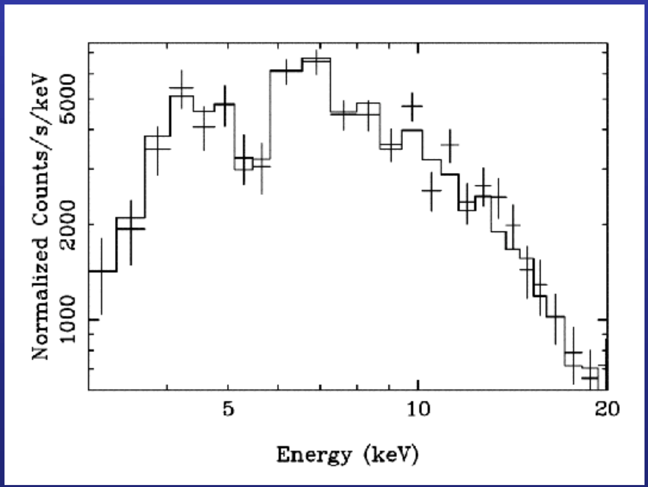
RXTE/PCA observations of bursts (Ibrahim et al. 2003):

broad absorption feature at **E=5 keV** + PL continuum;
proton cyclotron line at B=1e15 G ?

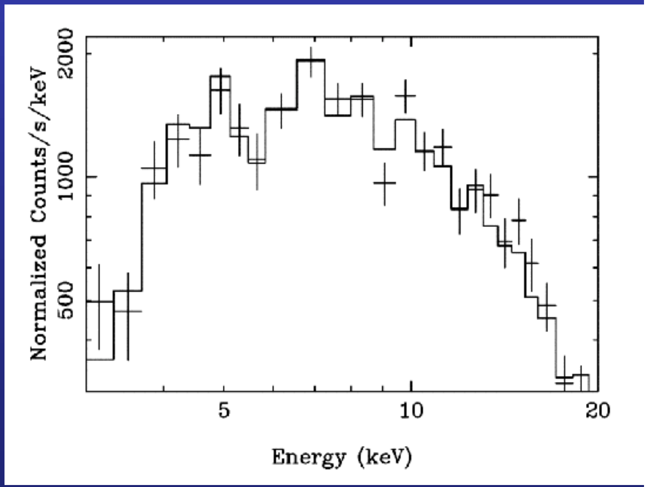
Burst 1



Burst 2



Burst 3



4. Neutron Stars in Transient LMXBs, in quiescence

(Cen X-4, Aql X-1, KS 1731-60, 4U 1608-52, ….)

Show thermal components best-described by Hydrogen atmosphere models [kT ~ 0.1 – 0.3 keV, R ~ 10 – 30 km] (e.g. Rutledge et al.)

Explanation: NS crust heated by pycnonuclear reactions in accreted matter; "incandescent luminosity" proportional to time-averaged accretion rate (Brown et al. 1998).

Useful tool to study superfluidity and fast neutrino emission in NS cores (Yakovlev & Levenfish 2002).

Can lead to rather precise measurements for NS radii (for qLMXBs in globular clusters).

Implications for Neutron Star Cooling

We have reasonable estimates for NS surface temperature and thermal luminosity for a number of NSs of different ages.

What can we infer confronting these results with cooling theories?

At $t = 10^2 – 10^6$ yrs, main cooling regulators are (1) neutrino emission mechanisms and (2) effects of baryon superfluidity on this emission

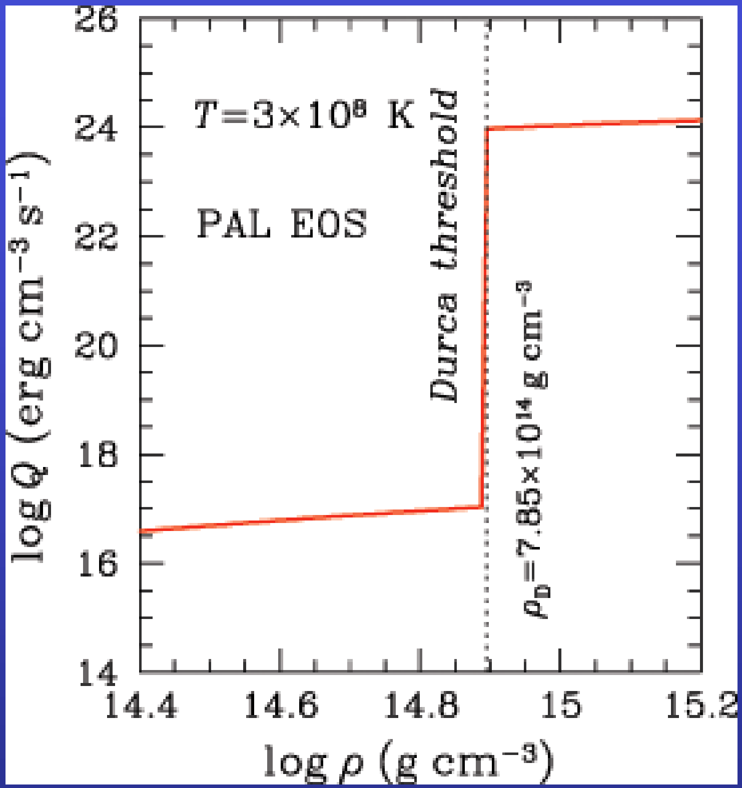
(1) $\rho < \sim 2\rho_{nuc}$: Modified URCA (Murca) + NN Brems.; "weak" mechanisms ◊ slow cooling

$\rho > \sim 2\rho_{nuc}$: Direct URCA (Durca) in nucleon matter or similar mechanisms in hyperon or exotic phases; strong mechanisms ◊ fast cooling

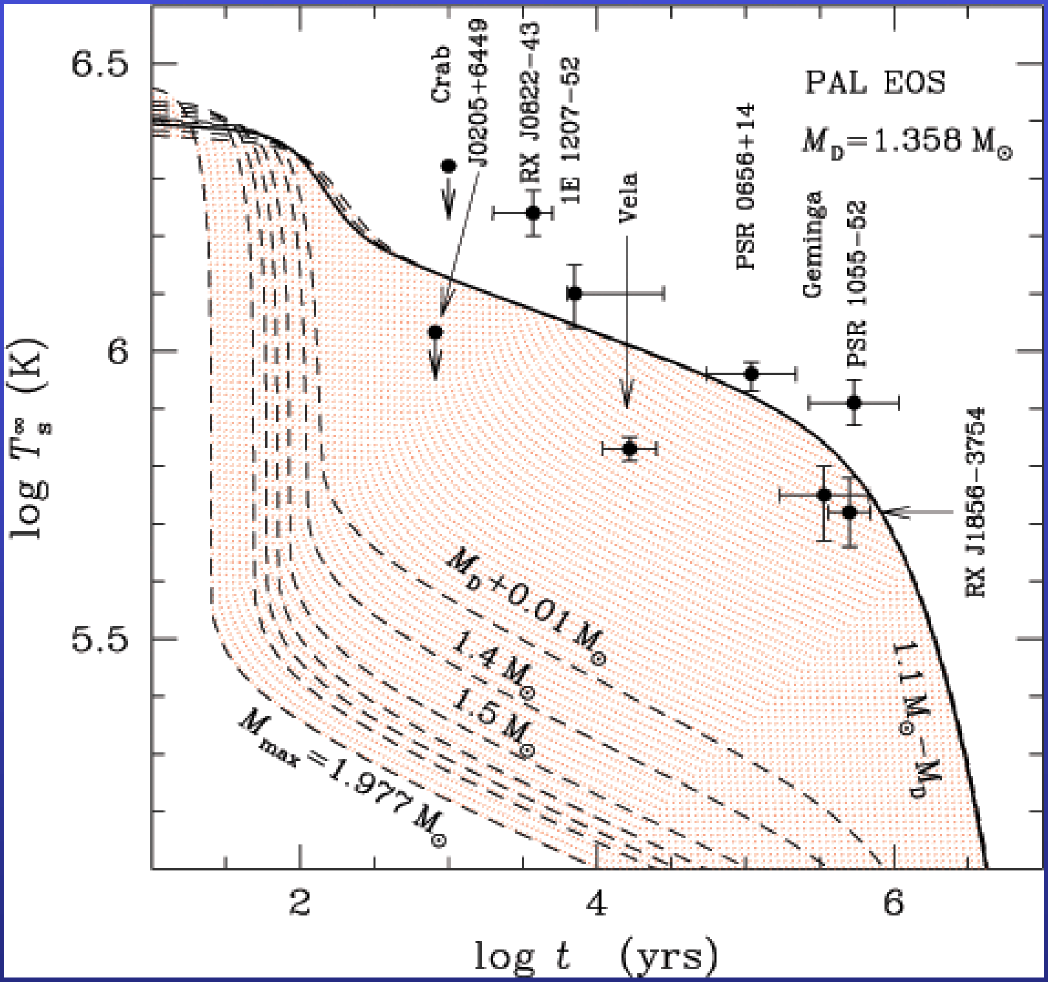
(2) superfluidity: reduces neutrino emission; different types (neutron, proton; triplet, singlet pairing,; …) with different poorly known critical temperatures $T_c(\rho)$

[Pictures below provided by D. Yakovlev]

Nonsuperfluid neutron stars with nucleon cores



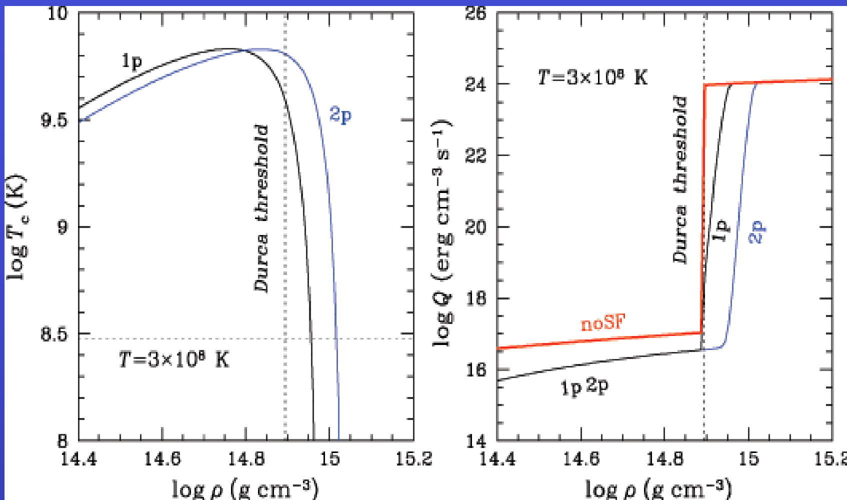
EOS: Prakash, Ainsworth, Lattimer, 1988



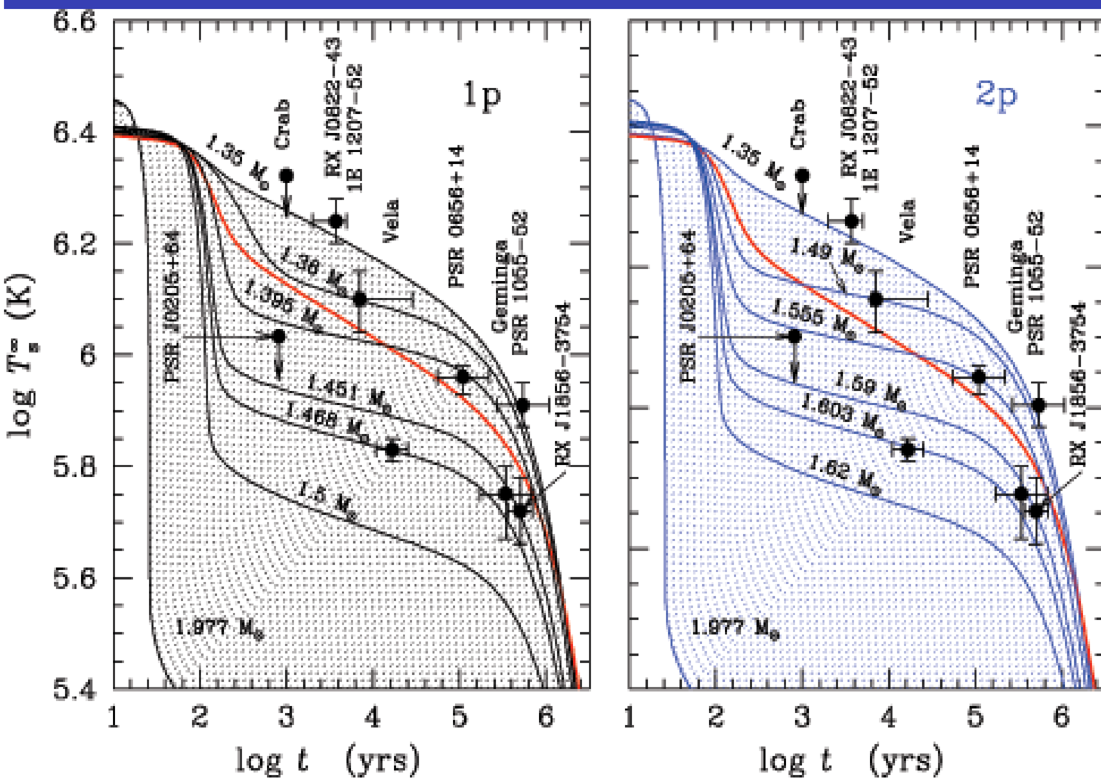
We **cannot** reconcile the data points with the cooling curves;

need superfluidity and/or exotic composition!

Superfluid Neutron Stars with Nucleon Cores



Critical temperature and neutrino emissivity vs. density, for two superfluidity models, 1p and 2p

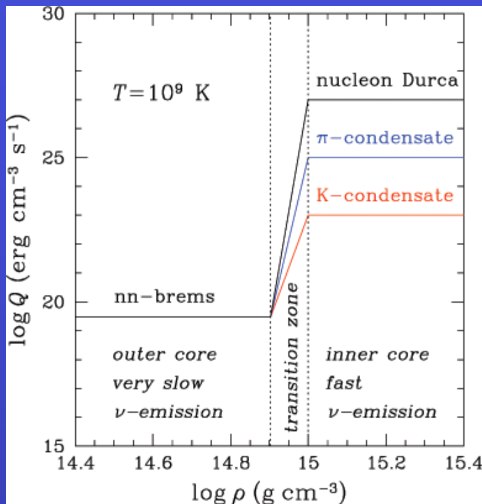


Data points **can** be reconciled with cooling curves.

Different NSs have different masses.

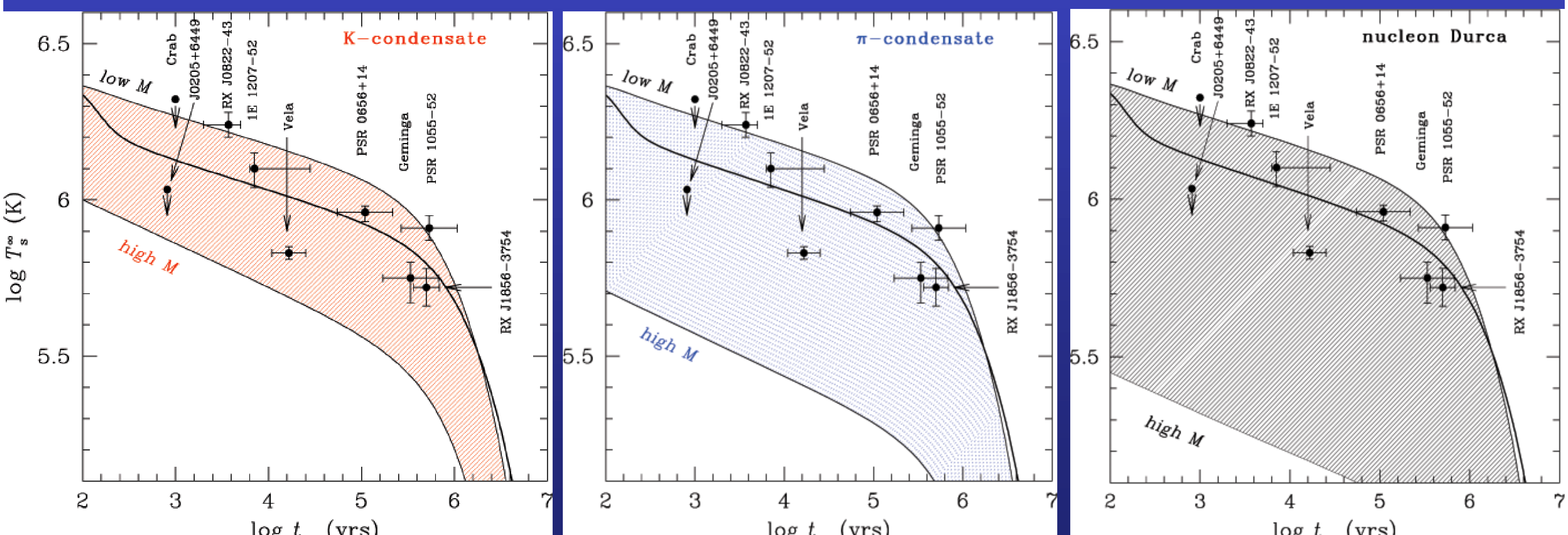
The masses inferred depend on the superfluidity model.

Nucleon cores vs. “exotic” cores



So far, the data are consistent with nucleon cores as well as with “exotic” cores.

More data points needed!



CONCLUSIONS

Thermal radiation from the NS surface has certainly been observed in many (~20) neutron stars, mostly in soft X-rays, with temperatures ~50 – 500 eV.

Most INSs have not shown spectral features. Continuum spectra give estimates of effective temperatures and R/D ratios.

Inferred **radii** are consistent with those expected for NSs in some cases; they are too small in other cases – either hot spots or solid surface with low emissivity or quark stars. Most promising for measuring R are qLMXBs in globular clusters and "dim" INSs

Comparison of **T(t)** with cooling theories shows that NSs have different masses, superfluid interiors; more observations are needed to establish presence/absence of "exotic" phases.

First spectral lines have been observed in several INSs:

Radio pulsars : **none** (but grating observations were short)

CCOs:	**1**	(absolutely firm)
Dim INSs:	**1** or **2**	(require confirmation)
AXPs:	**1**	(requires confirmation)
SGRs:	**1**	(looks firm)

To firmly infer NS properties, the lines must be identified – requires observations with high sensitivity and high spectral plus timing resolution; better understanding of atomic physics in very strong magnetic field and reliable models for emission from the NS surface/atmosphere.